

Advanced Prognostic Monitoring for FCS

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Problem

- **Key to survivability and reliability**
- **Event due to condition change**
- **Hidden in noisy, complex data**
- **Quantify change**
- **Practical technology:**
Quickly - (near) real time
Accurately - maximize total trues
Ambulatory device

Solution: data-driven analysis

Acquire Process-Indicative
Data

Remove Irrelevant
Artifacts

Capture Signature of Baseline
Dynamics

Capture Signature of Later
Snapshots

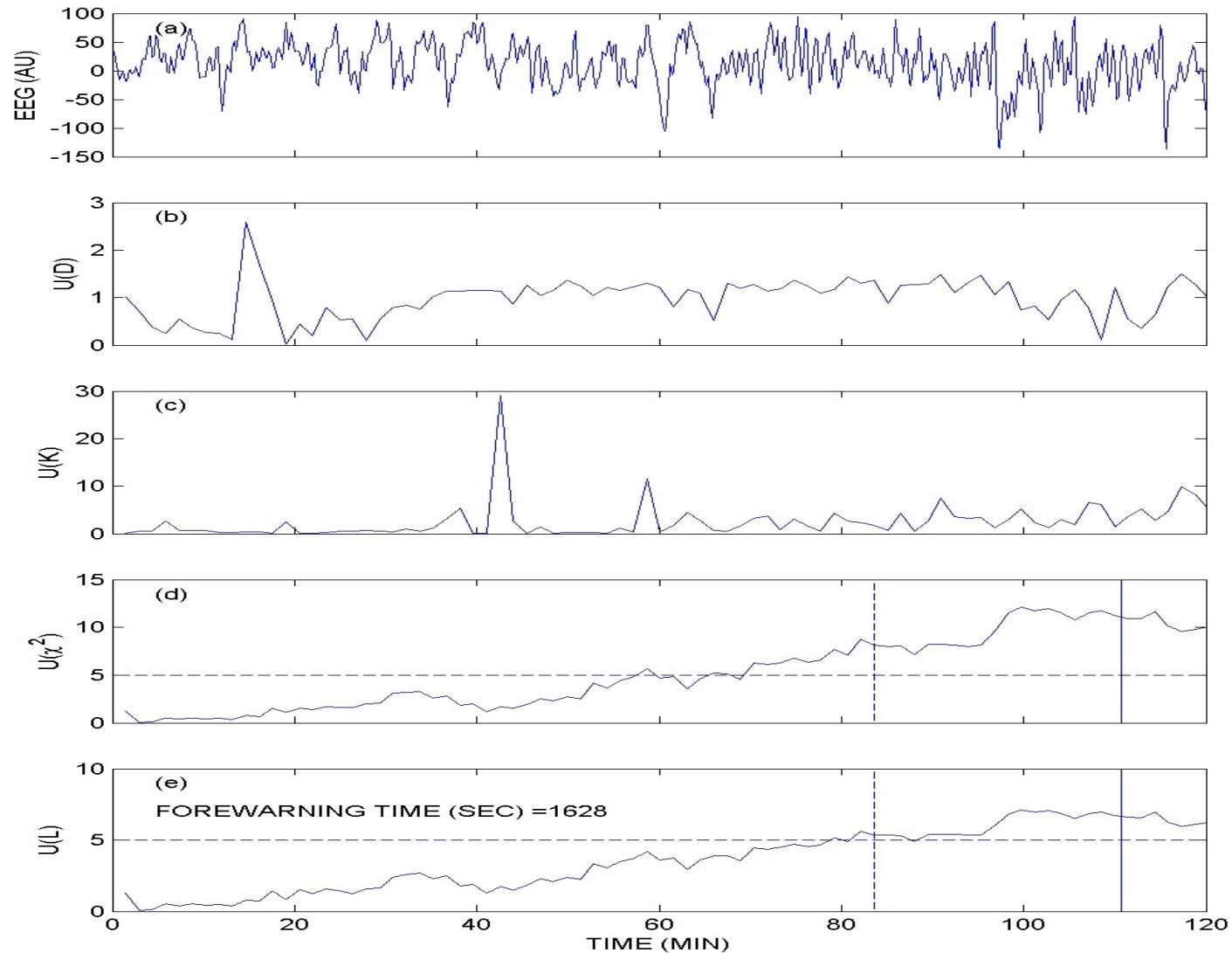
Dissimilarity Between Baseline &
Unknown

Forewarning for Significant
Dissimilarity

Example 1: EEG data

- **Biomedical Monitoring Systems Inc.**
- **Sample rate = 250 Hz**
- **19 channels of *scalp* data**
- **Band-pass filtered: 0.5 - 99 Hz**
- **Datasets span 5 000 - 29 500s**
- **60 datasets: 40 event, 20 non-event**
- **Multiple datasets: 30 from 11 patients**
- **36 females and 24 males: $4 \leq \text{years} \leq 57$**

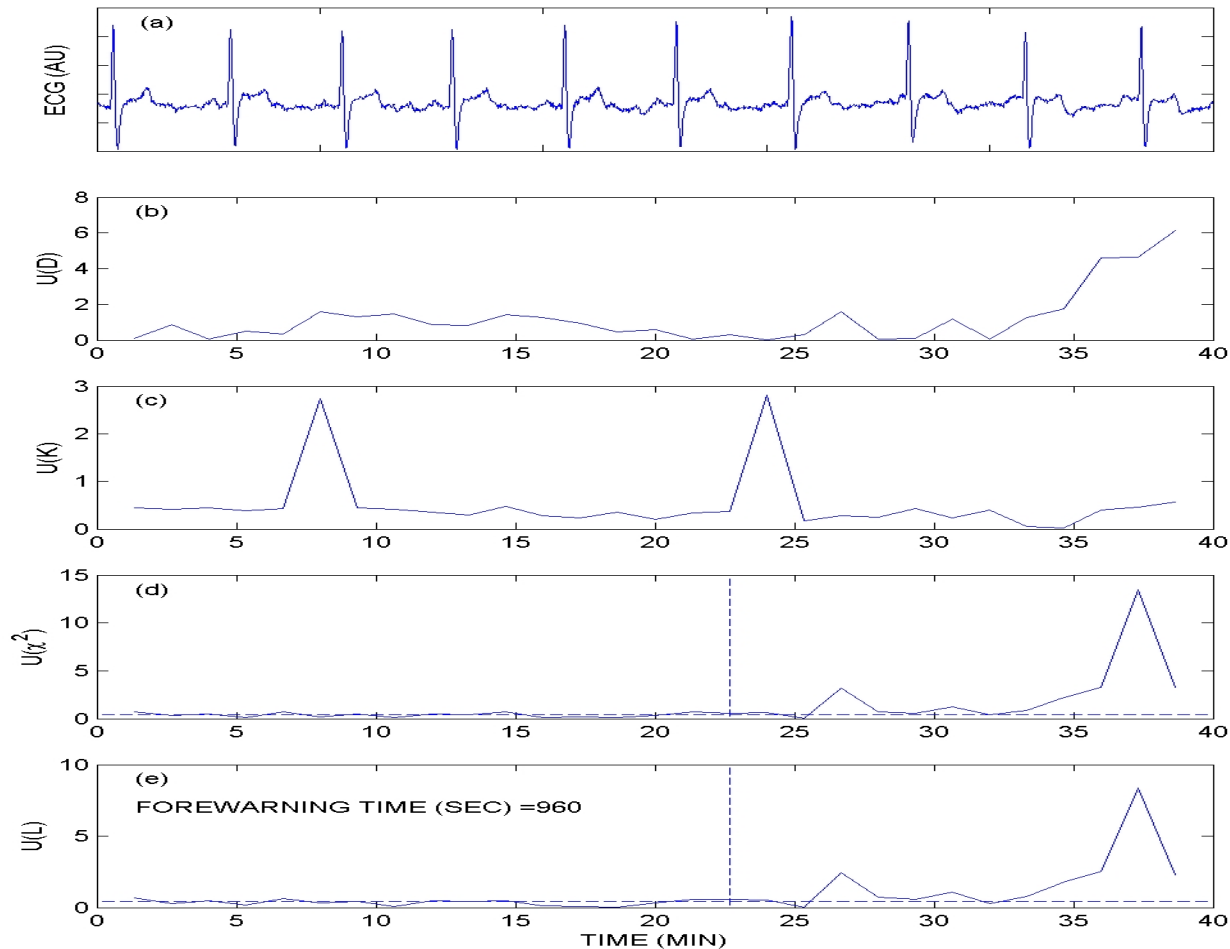
Example 1: EEG results



Example 2: cardiac events

- **5 electrocardiogram datasets**
 - **Digital data from Holter recordings**
 - **Analysis of one channel (250 Hz)**
 - **Datasets spanned <1 hour**
- **PS dissimilarity for forewarning**

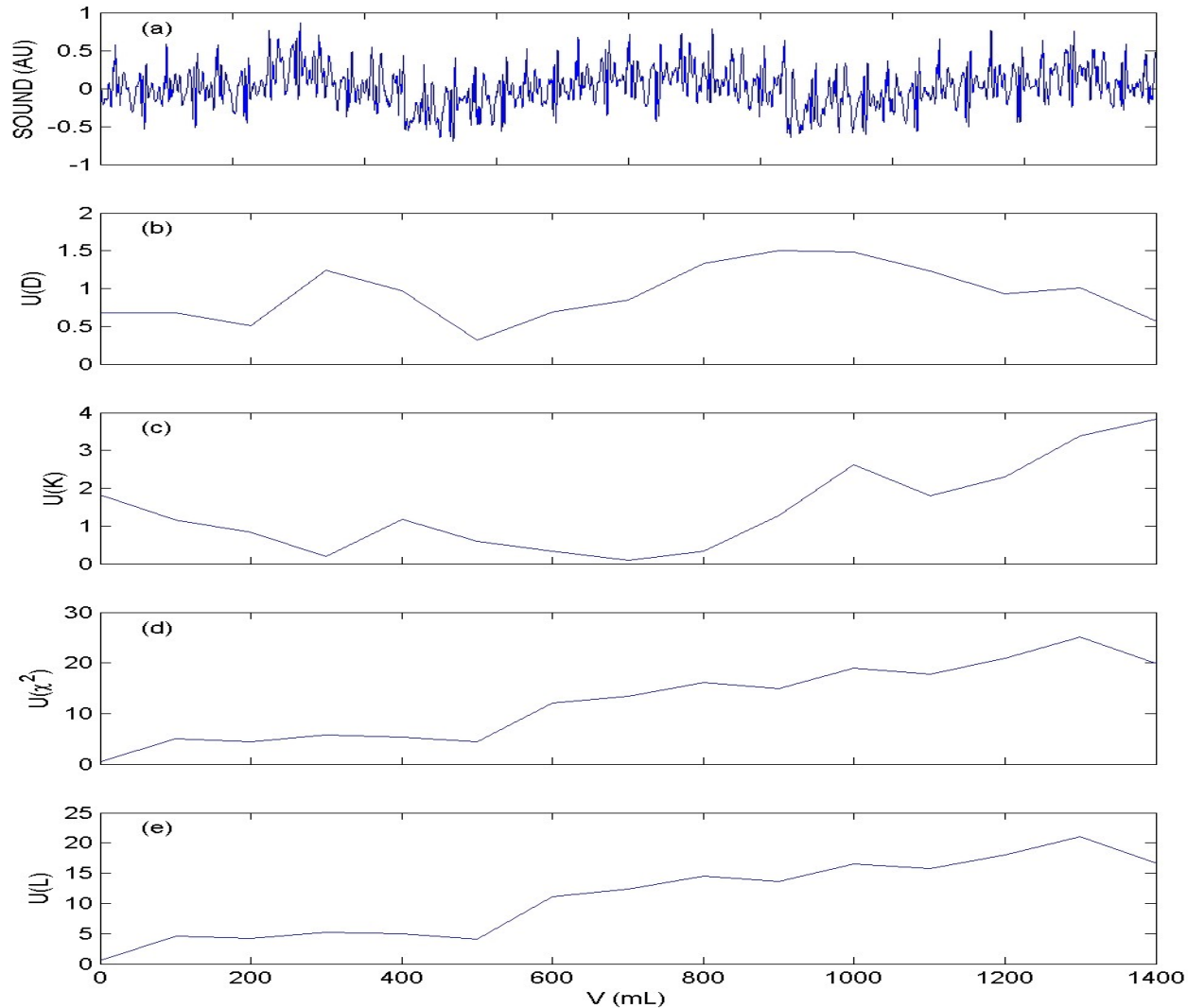
Example 2: cardiac results



Example 3: breathing difficulty

- **Test at Walter Reed Medical Ctr.**
 - anesthetized pig
 - 0 - 1400 ml of air into pleural space
 - surface (chest) stethoscope
 - sampling rate = 10 kHz
- **Basecase for normal breathing (0 ml)**
- **Testcases for 100 ml increments**

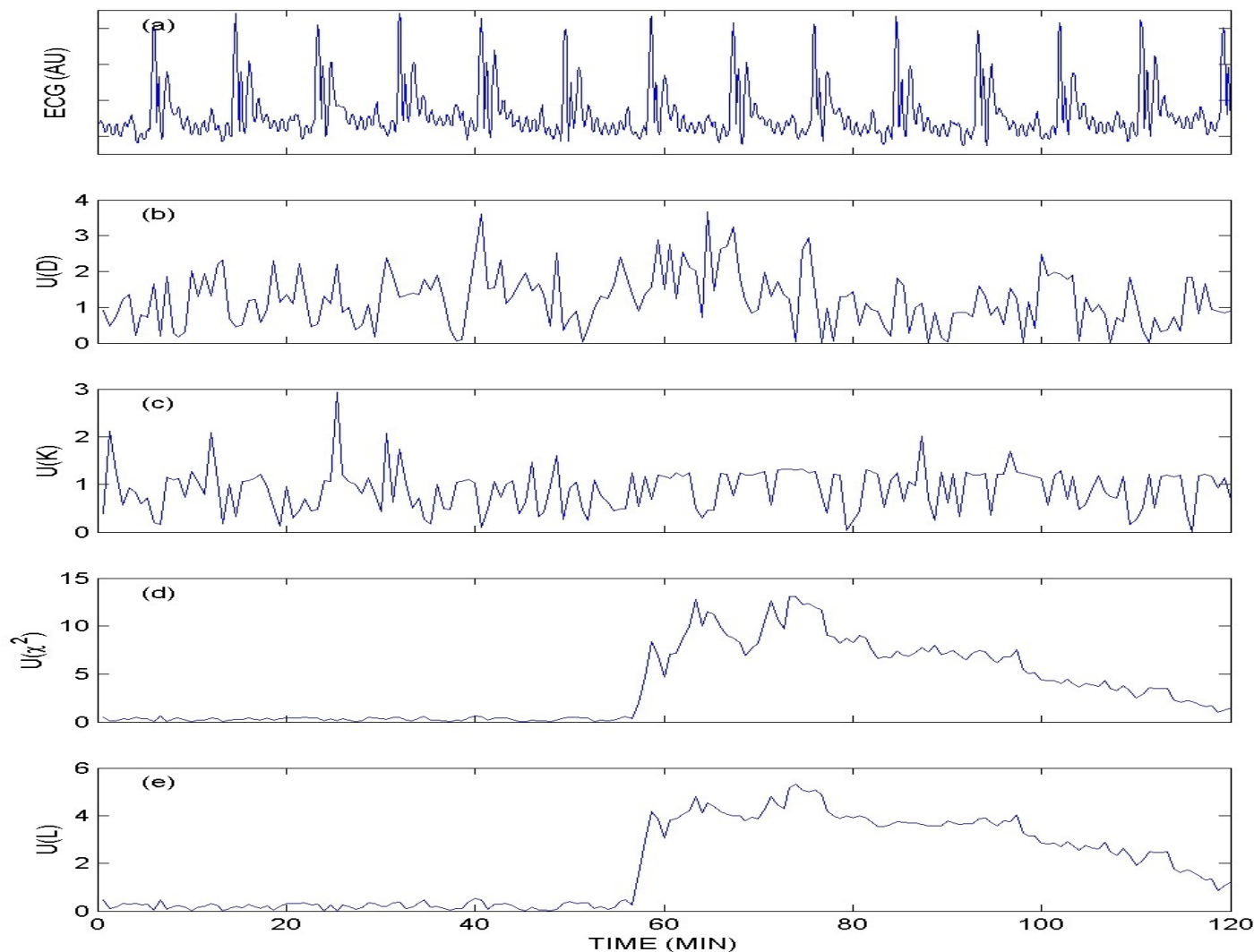
Example 3: breathing results



Example 4: sepsis onset

- **23 anesthetized rats at UTKMC**
 - **17 exposed to inhaled endotoxin**
 - **6 exposed to de-ionized water**
- **4 surface ECG electrodes (500 Hz)**
- **Test protocol (1.5-3 hours total)**
 - **30-60 minutes for baseline**
 - **30 minutes of *Salmonella* endotoxin**
 - **30-90 minutes of recovery**

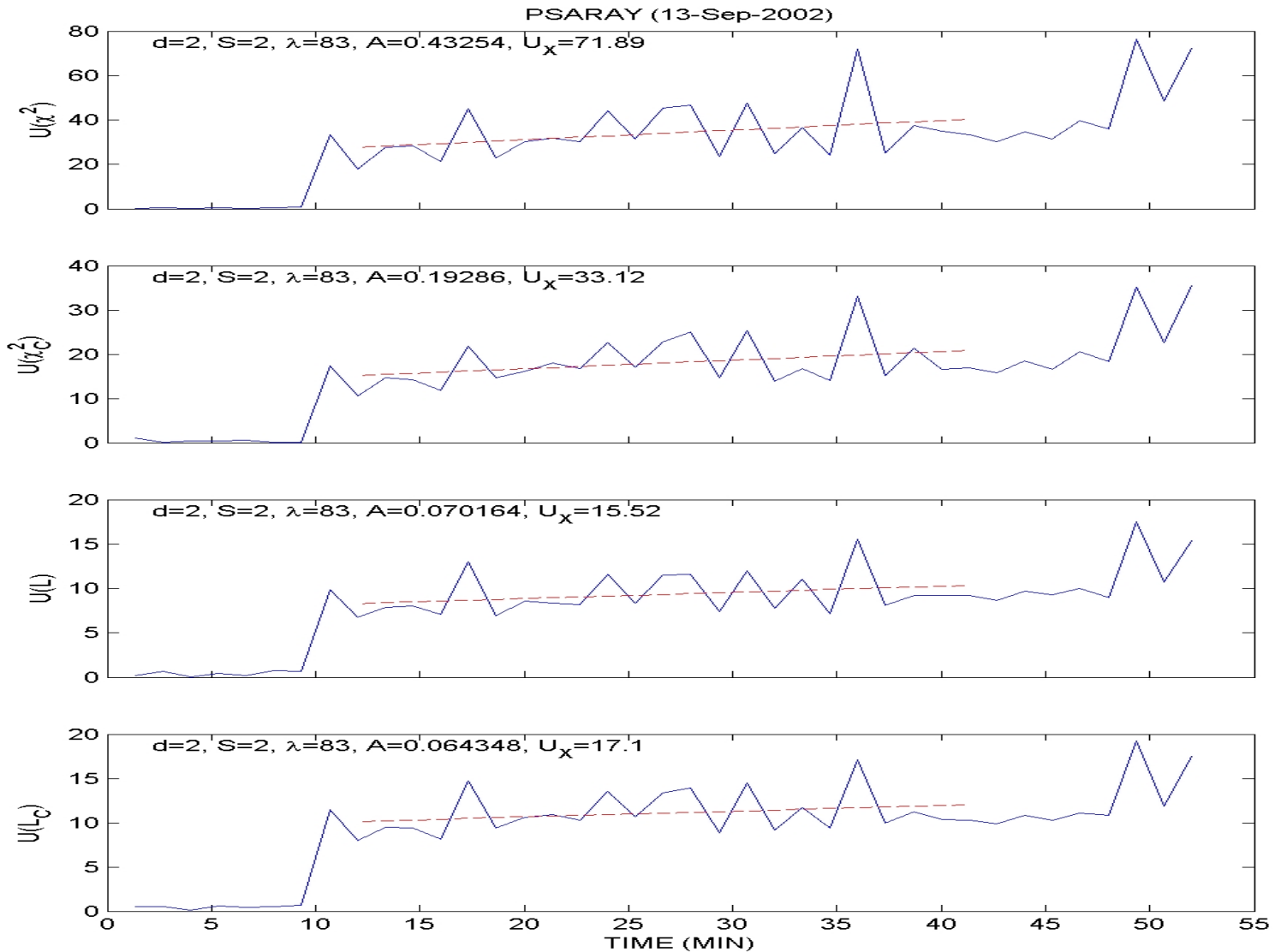
Example 4: sepsis results



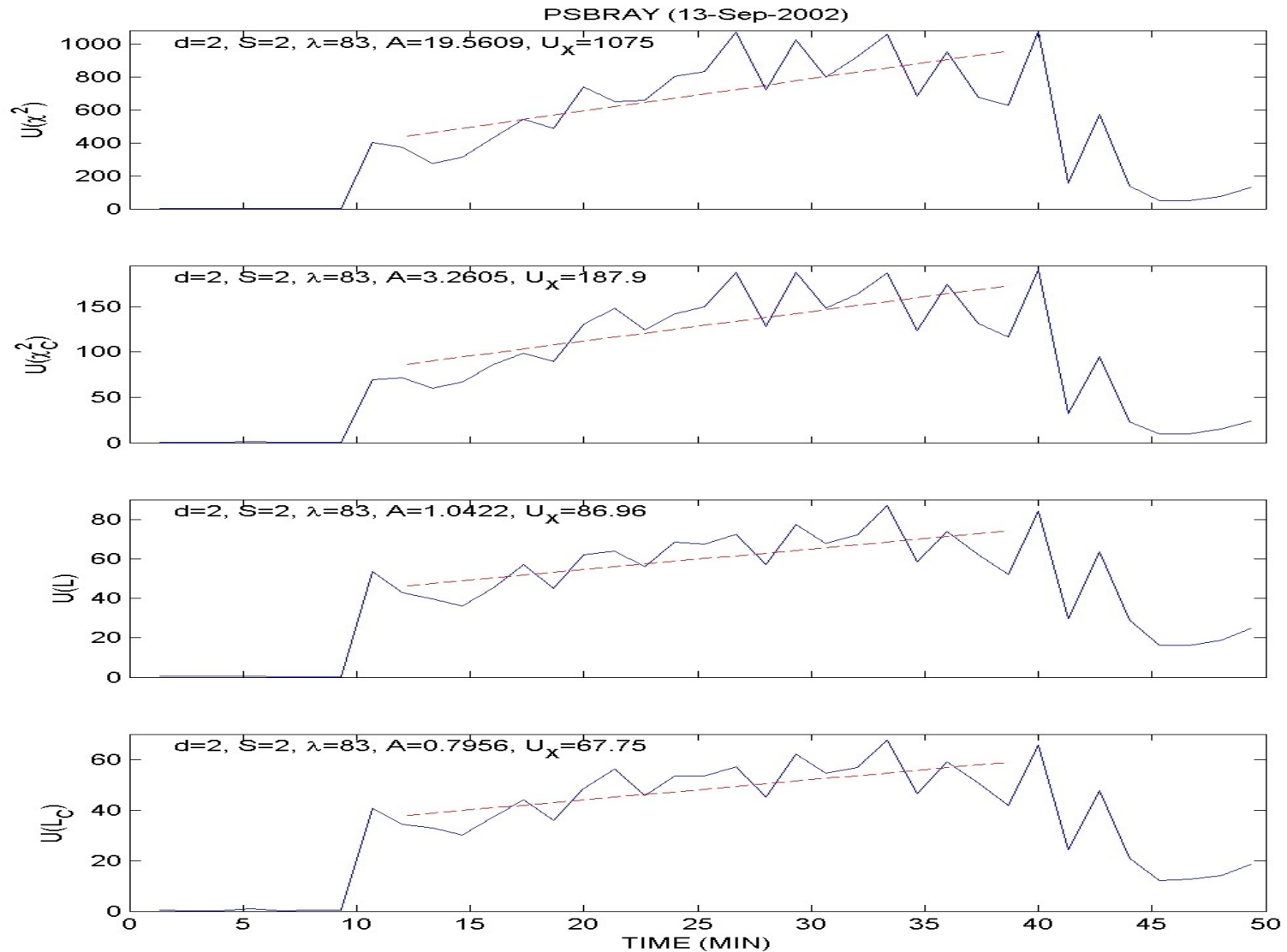
Example 5: fainting

- **Experiments at University of Ky**
- **ECG (250 Hz)**
- **Flat (10m); 70° tilt (60m); flat (5m)**
- **Two human subjects**
RAY/PSB (event), PSA (no event)
RUI/PSB (event), PSA (no event)

Example 5: fainting results (1)



Example 5: fainting results (2)



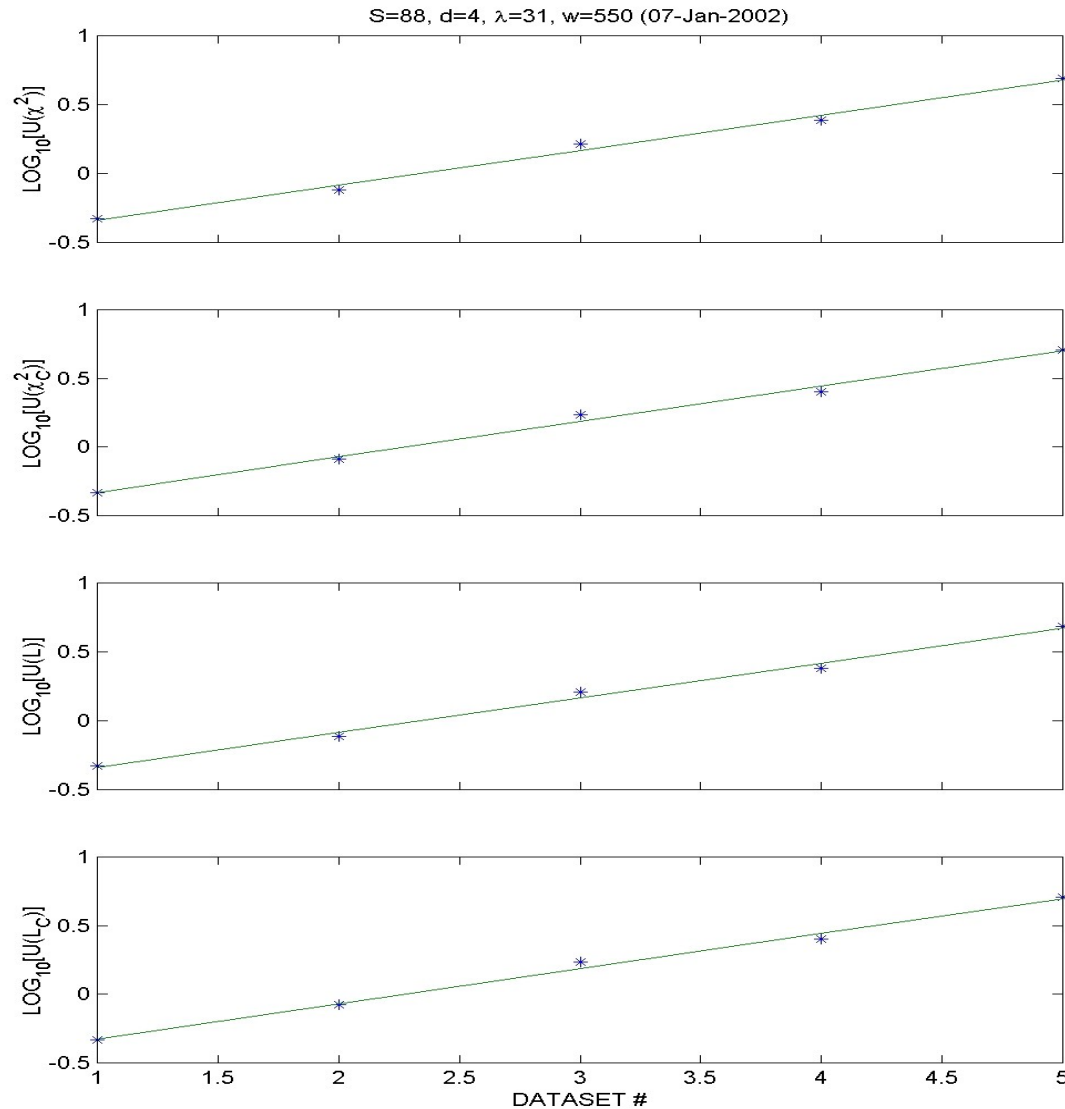
Example 5: fainting results (3)

- **RAY event**
much larger slope ($>12x$)
larger values ($\geq 4x$)
- **RUI event**
much larger slope ($>1149x$)
much larger values ($>34x$)

Example 6: seeded motor fault

- Nominal = no fault
- 1st fault = rotor bar cut half way thru
- 2nd fault = same rotor bar cut 100%
- 3rd fault = second rotor bar cut 100%
- 4th fault = 2 more rotor bars cut 100%
- Motor power at 40kHz

Example 6: motor fault results



Technology status: Now at TRL 5

- **High-fidelity technology integration**
- **Tests in simulated environment**
- **Failure forewarning ...**
- **Via analysis of archival data ...**
- **On desktop computer ...**
- **6 patents and two patents pending**

How to get from TRL5 to TRL7

- **On-line analysis of ...**
 - **Real-time data ...**
 - **On hand-held device ...**
 - **Via graphical user interface ...**
 - **Robust choice of parameters ...**
 - **Yielding accurate predictions...**
 - **That are event- and duration-specific...**
 - **And, analyst-independent**
- Marginal cost
for TLR6
prototype
- 

Conclusions: FCS prognostic

- **Data-driven, non-intrusive, fast**
- **Provides robust, timely forewarning**
- **Examples similar to soldier needs:**
 - **chest sounds ↔ abdominal wound**
 - **sepsis/ECG ↔ bio-warfare agent**
 - **epilepsy/EEG ↔ neurotoxin**
 - **fainting/ECG ↔ heat exhaustion**
 - **motor failure ↔ equipment failure**

QUESTIONS

- **Contact Lee Hively
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- **http://computing.ornl.gov/cse_home/staff/hively.shtml**

Backups

Outline

- **Problem: event forewarning/detection**
- **Solution: quantify condition change**
- **Specific biomedical applications**
- **Technology status**
- **Conclusions**
- **Questions**

Data-driven Analysis

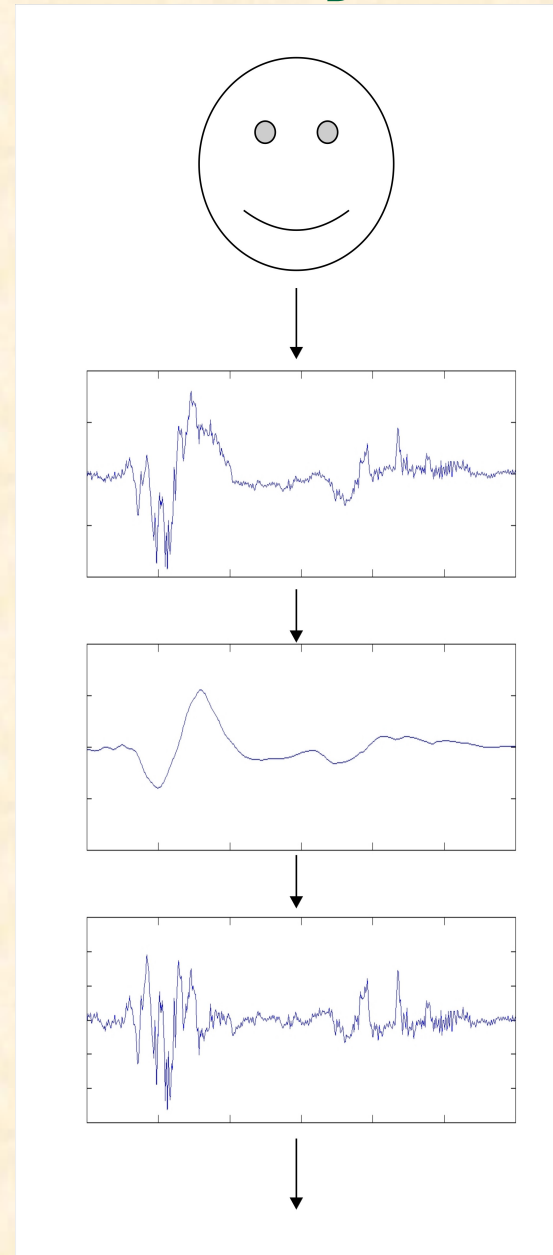
Time-series data:

x_i

**Raw (EEG) data
(3 s)**

**Artifact
(eyeblick)
removal**

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Data-driven analysis (Continued)

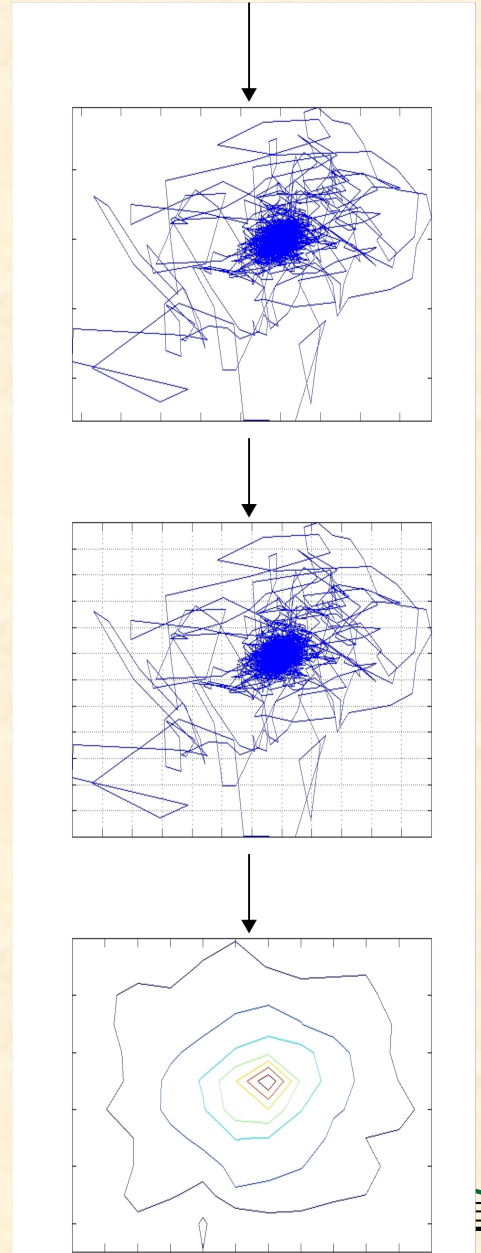
**Construct phase space
(PS):**

$y(i) = [x_i, x_{i+\lambda}]$ in 2D

$y(i) = [x_i, x_{i+\lambda}, \dots, x_{i+(d-1)\lambda}]$

**Distribution function
(DF) of PS points to
capture dynamics**

**Level contours of PS-DF
to quantify dynamics**



Solution: Time-Serial Data Analysis

- **Conventional statistical measures**
- **Traditional nonlinear measures**
 - Correlation dimension (complexity)**
 - Kolmogorov entropy (predictability)**
 - Mutual information (de-correlation)**
- **ORNL's patented measures**
 - Discrete statistical distributions**
 - Measures of dissimilarity**

Conventional Statistical Measures

- **Average:** $\underline{x} = (1/N) \sum_i x_i$
- **Standard deviation:** $\sigma^2 = \sum_i (x_i - \underline{x})^2/N$
- **Skewness:** $g_1 = \sum_i (x_i - \underline{x})^3/N\sigma^3$
- **Kurtosis:** $g_2 = \sum_i (x_i - \underline{x})^4/N\sigma^4 - 3$

Further Details

- **Divide data: non-overlapping subsets**
- **Check quality of data of each subset**
- **Remove artifact(s) from signal**
- **Create statistical distribution function**
- **$\underline{V}$ and σ_v from baseline dissimilarity**
- **Dissimilarity between baseline & unkn.**
- **Renormalization: $v = (V - \underline{V})/\sigma_v$**

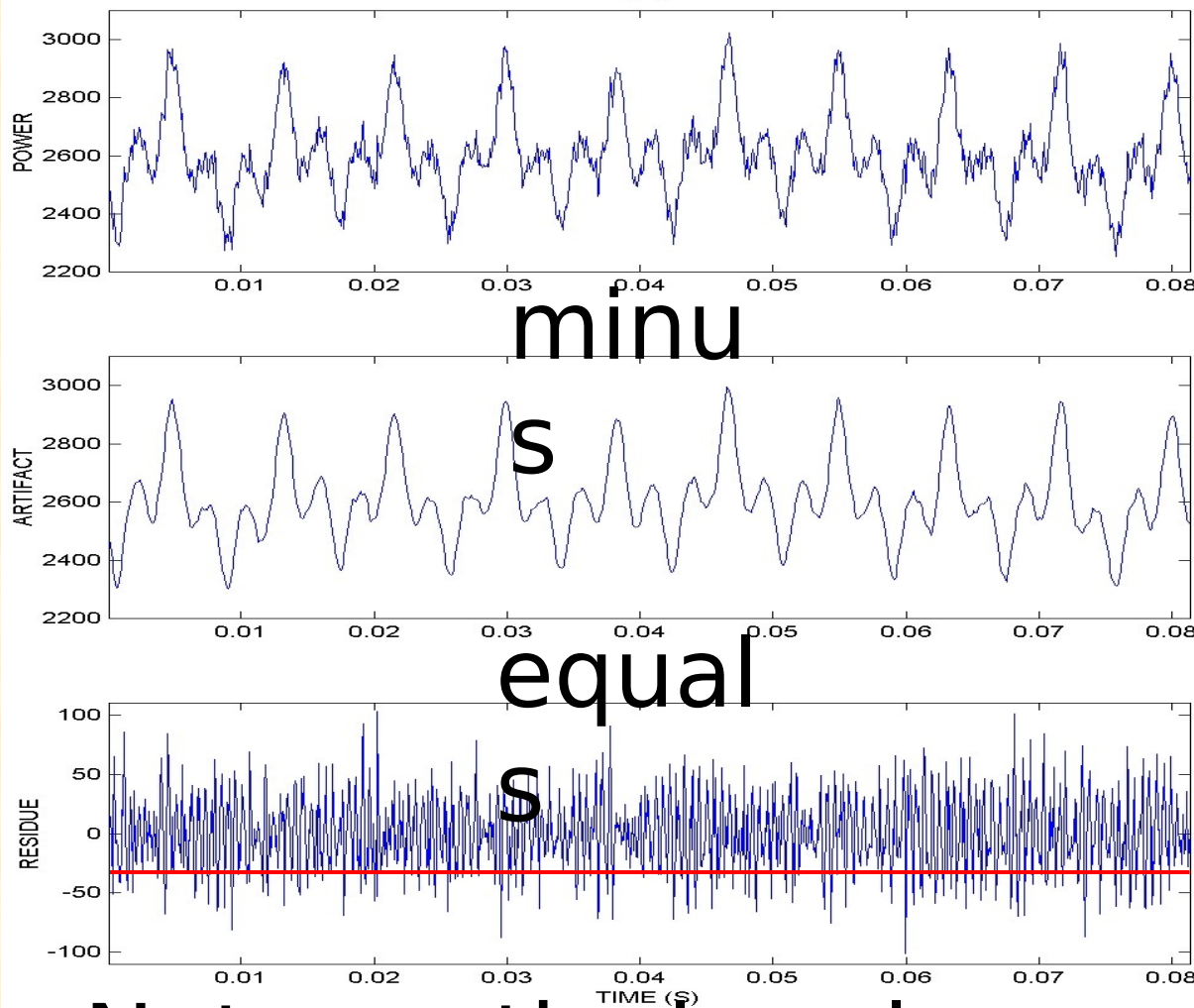
Data Quality Check

- **Proper number of data points?**
- **Significant period(s) with no change?**
- **Is sampling rate too low?**
- **Monotonic increases or decreases?**
- **Excessive quasi-periodicities?**
- **Excessive noise?**
- **Data correctly scaled?**
- **Consistent signal amplitude?**

Artifact removal

- **Window of $2w+1$ points of raw data (e_i)**
- **Least squares fit of parabola to e_i**
- **Central point as estimate of artifact (f_i)**
- **Artifact-filtered data: $g_i = e_i - f_i$**
- **Move window by one point and repeat**

Example of Artifact Removal



Raw
data

Artifac
t

Artifa
ctfilte
red
data

Note vertical scale
change

Dynamical Reconstruction

- **Data at discrete times: $x_i = x(t_i)$**
- **d -dimensional phase space (PS):
 $y(i) = [x_i, x_{i+\lambda}, \dots, x_{i+(d-1)\lambda}]$**
- **PS bins: occurrence frequency
(Un)changing DF with (un)altered dynamics**
- **Nonlinear measures from PS-DF**

Phase-Phase Distribution Function

- **Symbolize:** $x_i = S(x_i - x_{\min}) / (x_{\max} - x_{\min})$
- **PS vector as base-S identifier**
$$y(i) \rightarrow z(i) = \sum_k S_{i+(k-1)\lambda} S^{k-1}$$
$$Y(i) \rightarrow Z(i) = z(i) + S^d z(i + \mu)$$
- **Tabulate occurrence in each PS bin**
- **P_k = baseline distribution (DF)**
- **Q_k = DF of testcase**

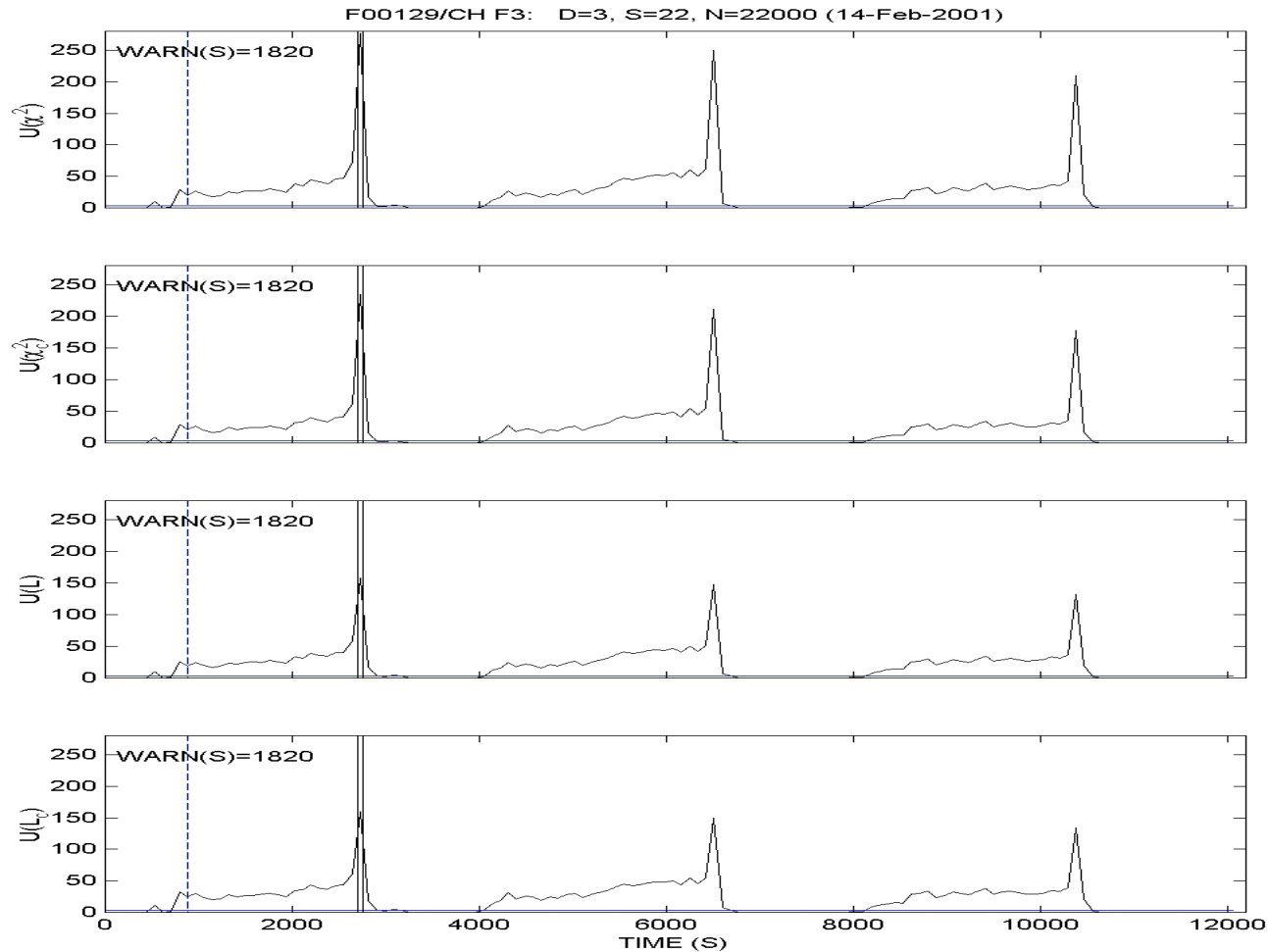
Dissimilarity Measures

- $\chi^2 = \sum_k (\mathbf{P}_k - \mathbf{Q}_k)^2 / (\mathbf{P}_k + \mathbf{Q}_k)$
- $\mathbf{L} = \sum_k |\mathbf{P}_k - \mathbf{Q}_k|$

visitation frequency & location in PS

- **Dissimilarity measures:**
subtract, then integrate ... **sensitive**
- **Traditional measures:**
integrate, then subtract ...
insensitive

Dataset F00129: Three Seizures



Seeded Fault in Three-Phase Electric Motor

Manufacturer: Allis Chalmers	Bearing type: sleeve
Rated voltage: 4160	Nameplate current:
100 a	
Rated HP: 800	Number of rotor bars: 94
Winding type: form wound	Number of stator slots: 40
Phases: 3	Hertz: 60
RPM: 710	Motor type:
induction	
Insulation class: F	Poles: 10
Enclosure: TEFC	Bar configuration: copper

- Nominal = no fault
- First fault = rotor bar cut half way through
- Second fault = same rotor bar cut 100% through
- Third fault = second rotor bar cut 100% through
- Fourth fault = two more rotor bars cut 100%

Convergence of Technologies for Spiral Integration

- **GPS for accurate location of data source**
FCC mandate: GPS mobile phone location to 911
- **PDA/DSP for smart data acquisition and processing ...**
commercial toolkit to program PDA
- **Mobile phone to transmit data**
Above 3 in “Digital Angel,” (*NYTimes*, 2/22/01, DJ Wallace)
Wireless communications for extreme envir (ORNL 2003)
- **Power from biofuel cell** (*Science*, 17 May 2002, p1222)
Thin-film rechargeable lithium battery (ORNL 2003)
- **Microcantilever-based sensors** (ORNL 2003)
Lab-on-a-chip (ORNL 2003)

Convergence of Technologies: Smart Sensors

- **GPS for accurate location of data source**
FCC mandate: GPS mobile phone location to 911
- **PDA/DSP for smart data acquisition and processing ...**
MATLAB toolkit to program DSP in ANSI C
- **Mobile phone to transmit data**
Above 3 in “Digital Angel,” (*NYTimes*, 2/22/01, DJ Wallace)
Wireless communications for extreme envir (ORNL 2003)
- **Power from biofuel cell** (*Science*, 17 May 2002, p1222)
Thin-film rechargeable lithium battery (ORNL 2003)
- **Microcantilever-based biosensors** (ORNL 2003)
Lab-on-a-chip (ORNL 2003)

MANY OTHER POTENTIAL APPLICATIONS

- **Scalp EEG for ...**
 - **CNS pathologies, drug/chemical effects, head trauma, shock**
 - **evoked response for CNS/sensory diagnostic**
 - **alertness/fatigue/stress/performance**
 - **hands-free computer control (removal of muscular artifacts)**
- **EKG for forewarning of cardiac fibrillation**
- **Lung sounds for pulmonary pathology**
- **Other physiological data (body sounds, EMG, etc.)**
- **Data fusion (EEG/EKG/body sounds ...) for physiological pathologies**
- **Muscle tremors (3-axis acceleration) for neuromuscular pathologies**
- **Condition monitoring of machines for failure forewarning**
- **Fetal monitor during labor and delivery**
- **Monitor for SIDS-risk patients**

Vision for Advanced Biomedical Analysis

- **New sensors will provide ...**
- **Wealth of data**
sounds, EEG, ECG, blood, images, etc.
for ...
- **Fusion of multi-channel data from ...**
- **Dynamics of metabolic/sensory networks with ...**
- **Near-real-time response, yielding ...**
- **New medical science and ...**
- **Lower cost, higher quality care of patients**

Correlation Dimension

d = dimensionality

R = radius about central point = $|x_i - x_0|$

n = number of points within radius $\propto R^d$

$\delta_{ij} = \max |x_{i+k} - x_{j+k}|$ over $0 \leq k \leq m-1$

m = average number of points per cycle

δ_n = scale length associated w/noise

M = # randomly sampled pt pairs

$D = \{(-1/M) \sum_{ij} \ln[(\delta_{ij} - \delta_n)/(\delta - \delta_n)]\}^{-1}$

Kolmogorov Entropy

$K = -f_s \ln(1 - 1/\underline{b}) = \text{bits lost per sec}$

$f_s = \text{digital sampling rate}$

$\underline{b} = (1/M) \sum_{ik} b_{ik}$

$b_{ik} = \text{number of timesteps for two nearby points to diverge from } |x_i - x_k| \leq \delta \text{ to } |x_i - x_k| > \delta$

$\delta = \text{scale length in data (multiple of } a)$

$a = (1/N) \sum_i |x_i - \underline{x}| \text{ and } \underline{x} = (1/N) \sum_i x_i$

Mutual Information Function

$I(R,S)$ = predictable bits in S from R
 $= I(S,R) = H(R) + H(S) - H(R,S)$

$H(R) = - \sum_i P(r_i) \log_2[P(r_i)]$

$H(R,S) = - \sum_{ik} P(r_i, s_k) \log_2[P(r_i, s_k)]$

R, S = all possible values of r_i and s_k

$P(r_i)$ = probability associated with r_i

$P(r_i, s_k) =$ joint probability of r_i and s_k

Typically use first minimum (M_1) in I

Choice of PS Parameters

<u>Algorithm step</u> <u>Choice</u>	<u>Parameters for this step</u>	<u>Allowed range</u>	<u>Typical values</u>
Acquire analog data	# data channels (C)	$1 \leq c \leq 32$	1
Digitize data	data points per cutset (N) $N = 25,000$	variable	$1 \leq N/10^4 \leq 7$
fixed	data sampling rate (f_s) $f_s, f_s/2, f_s/3, \dots$	f_s	f_s
fixed	digital precision in bits (B)	fixed	fixed by acquisition
	anti-aliasing filter param.	fixed	fixed by acquisition
Remove artifact f_{peak}	filter half width (w)	$1 < w < (N-1)/2$	$w = f_s/(4.4 f_{\text{peak}})$ $w = f_s/(4.4$
	raw (R)		
	artifact (A)	R, A, or AF	variable A
	artifact-filtered (AF)		
Symbolize data	number of symbols (S)	$2 \leq S \leq 2^B$	variable
equiprobable	uniform; equiprobable	U or E	equiprobable

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operational

PS dimensions (d) $2 \leq d \leq 26$

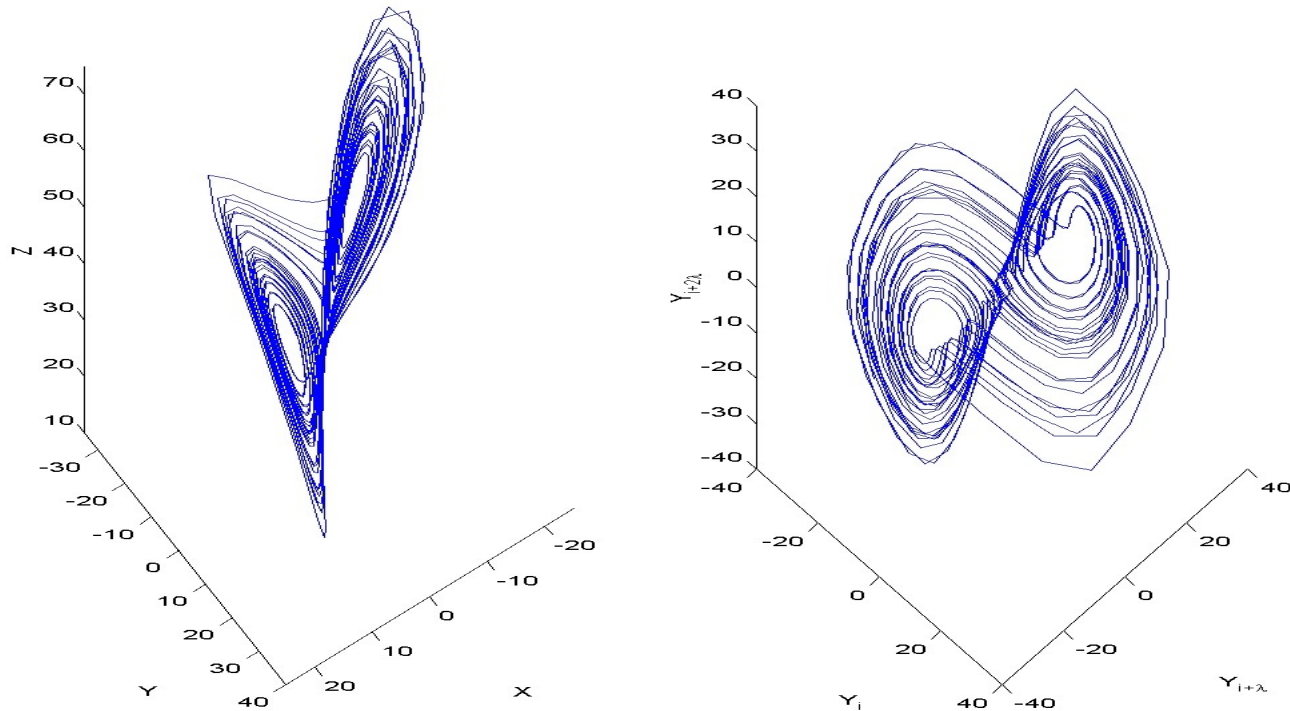
variable



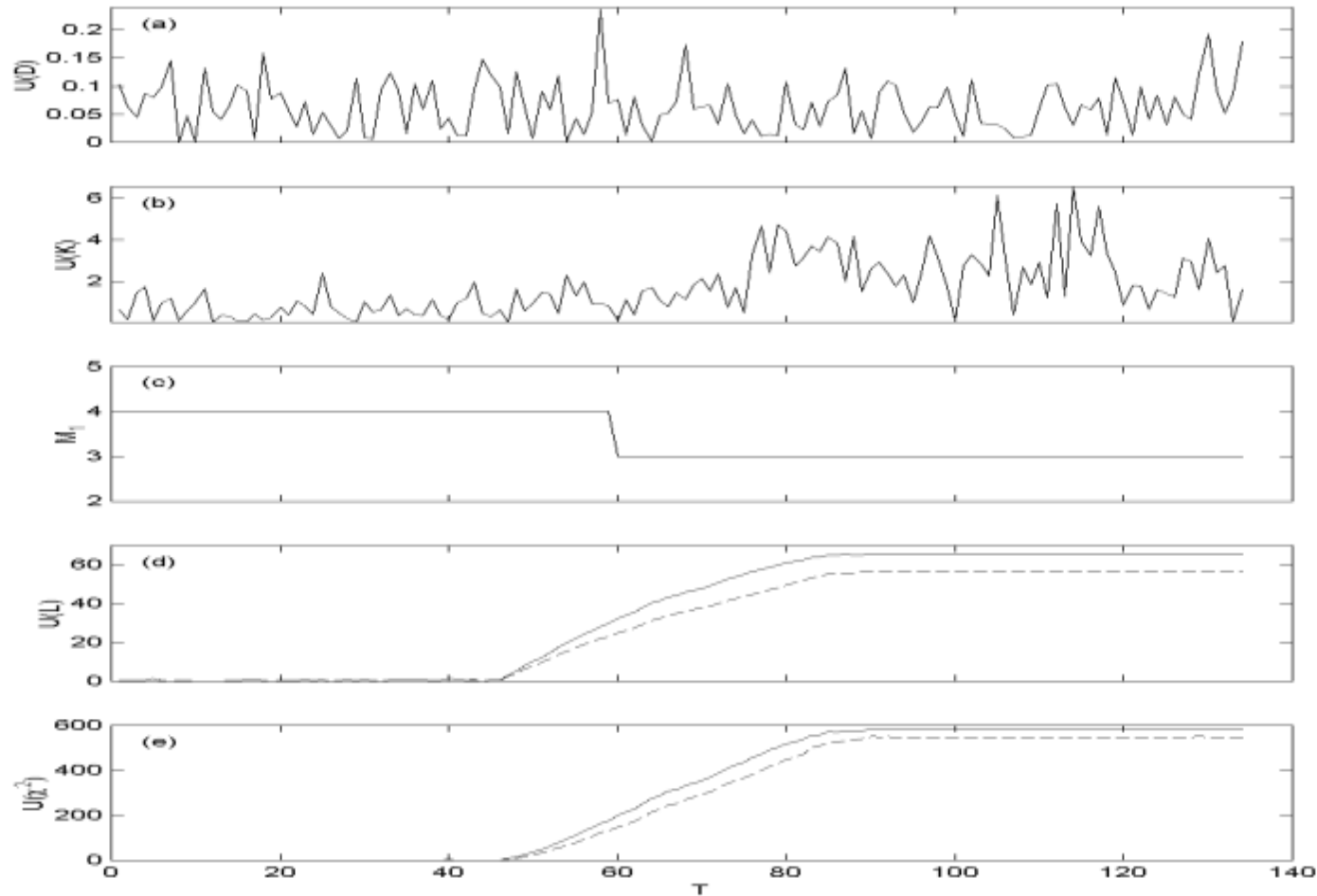
Lorenz Model

- **Three (3) simultaneous ODEs:**
$$\frac{dx}{dt} = a(y - x)$$
$$\frac{dy}{dt} = rx - y - xz$$
$$\frac{dz}{dt} = xy - bx$$
- **Parameters: $a=10$, $b=8/3$, $25 \leq r \leq 90$**
- **Basecase for $r=25$**
- **200,000 points for each value of r**
four non-overlapping sets of 50,000 points

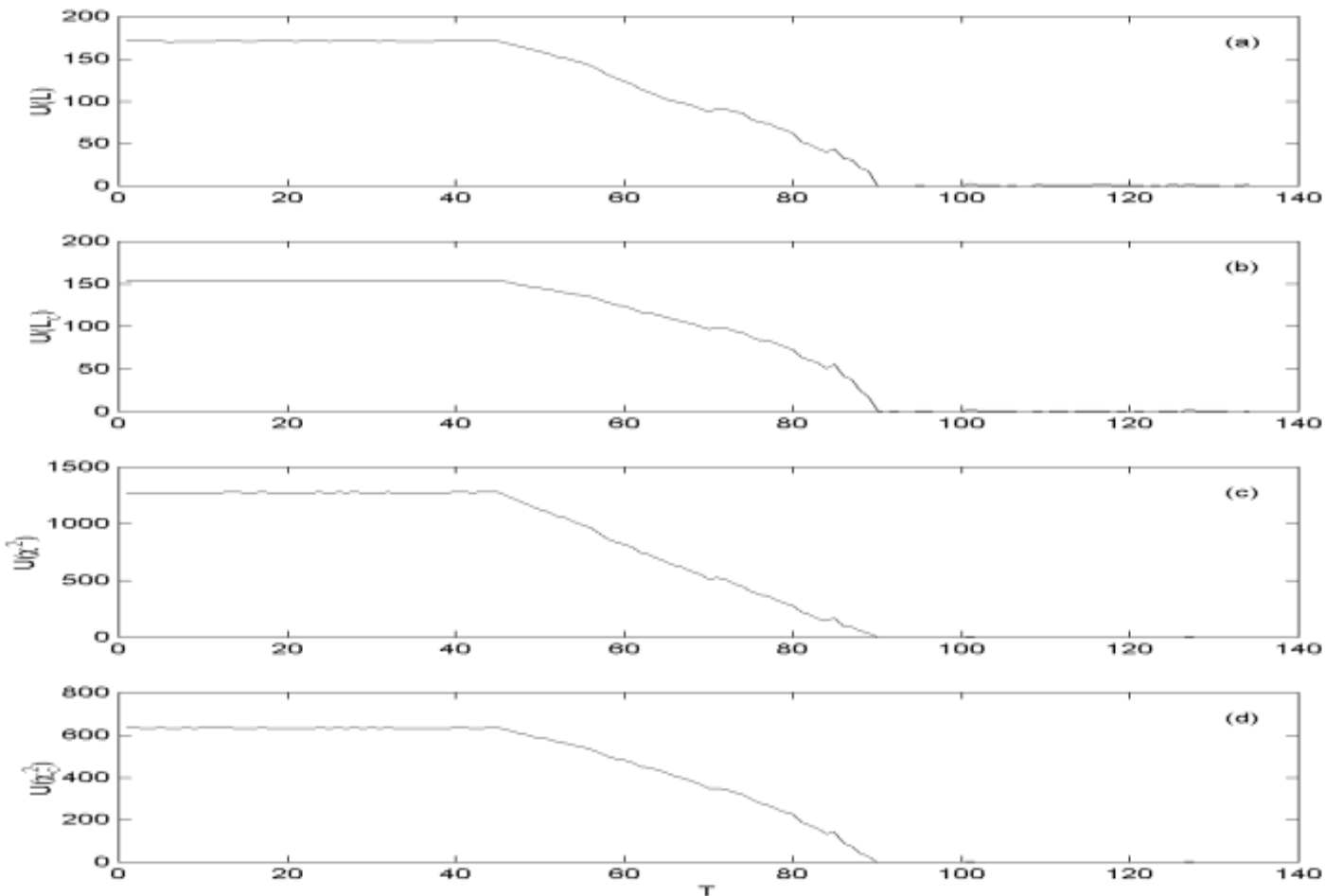
Phase Space for Lorenz Model



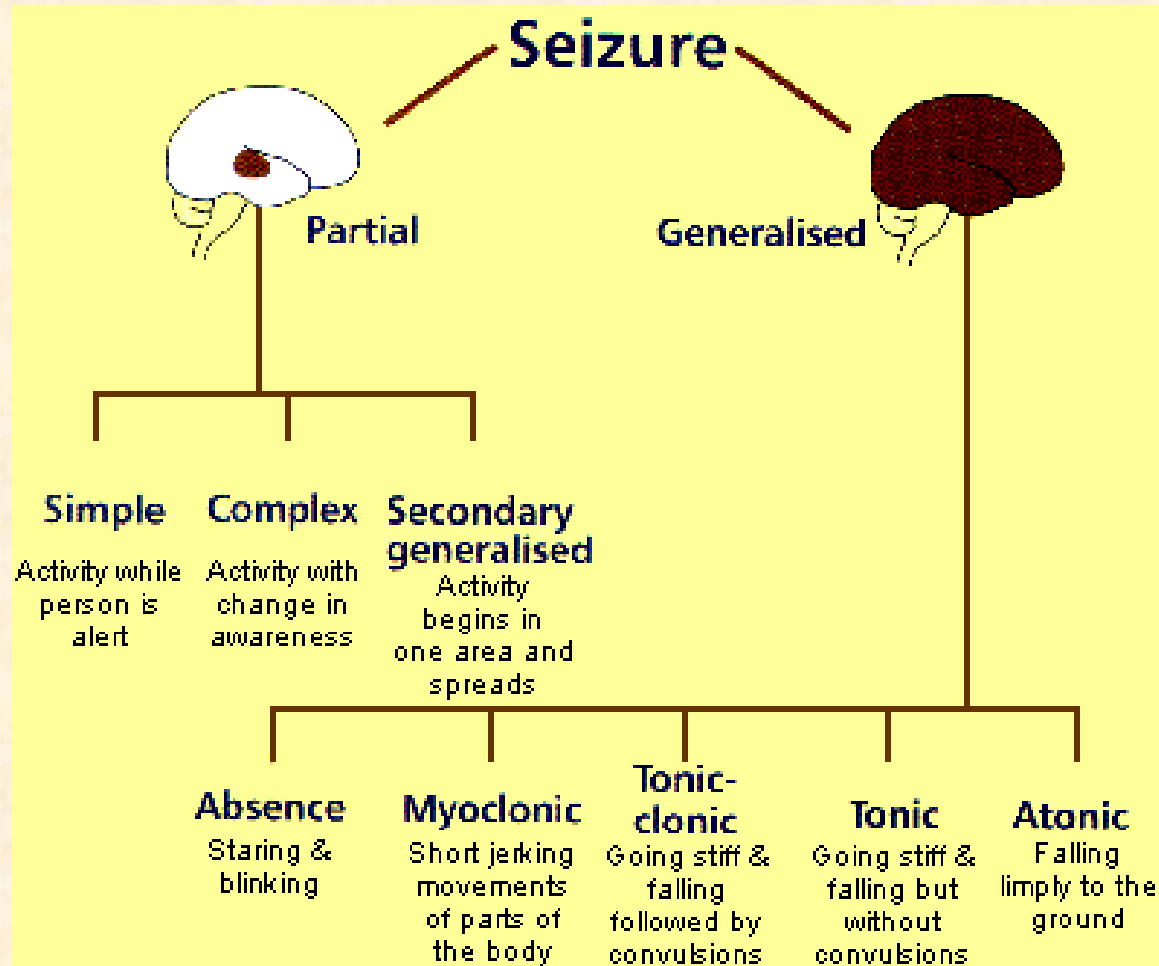
Results for Lorenz System



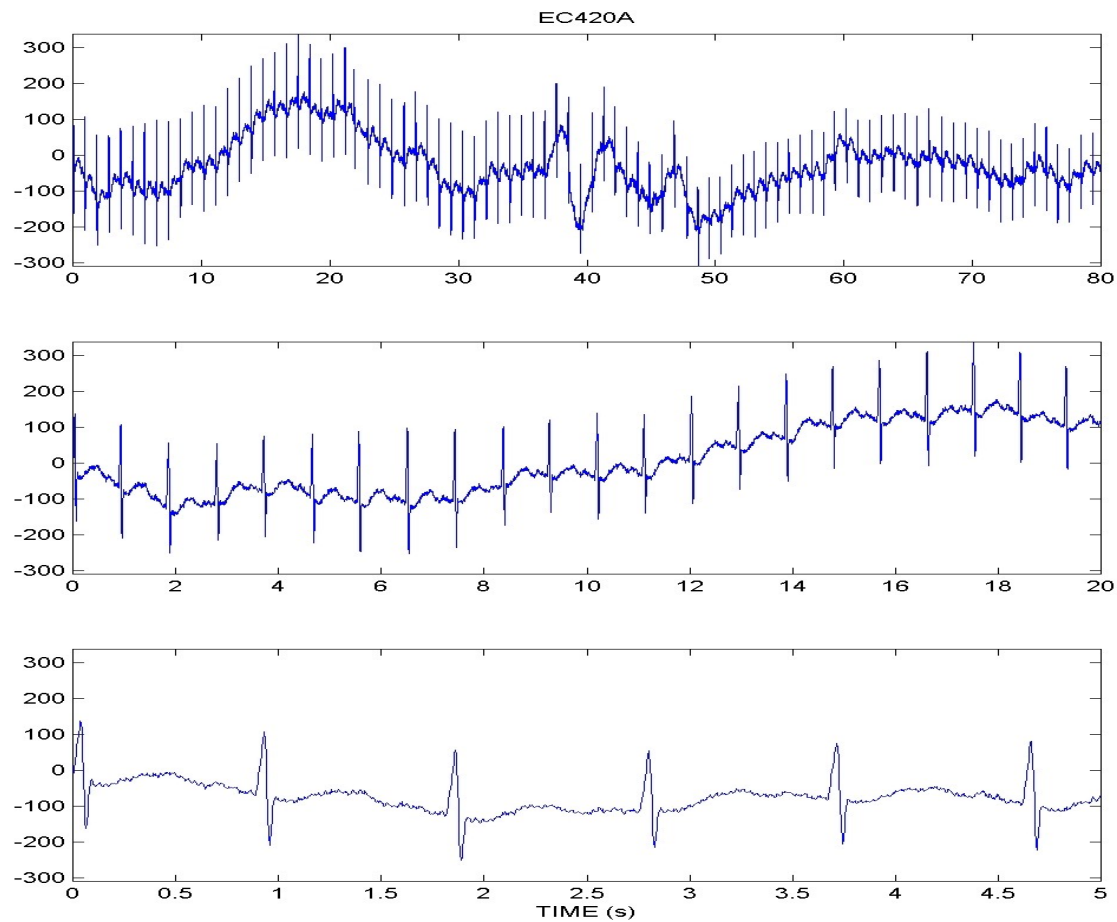
Reverse Results for Lorenz System



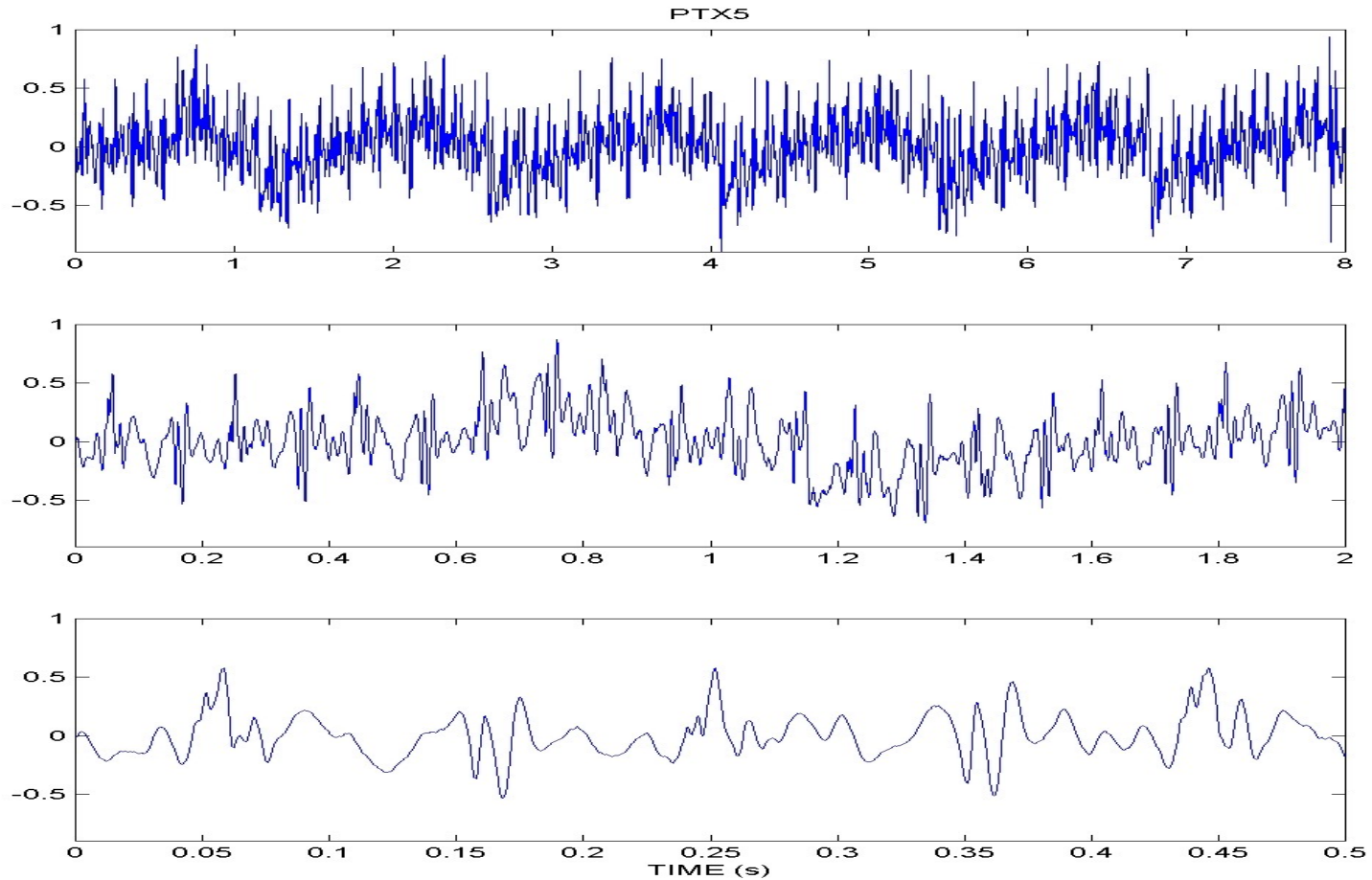
Seizure Types



RAW EKG DATA



RAW DATA (PTX5)



Publications on lung sounds

- 1. R.C. Ward, K. L. Kruse, G. O. Allgood, L. M. Hively, K. N. Fischer, N. B. Munro, and C. E. Easterly, "Virtual Human Project" in "Visualization of Temporal and Spatial Data for Civilian and Defense Applications" (eds. G.O. Allgood and N. L. Faust) *Proc. SPIE* **4368** (2001) 158-167.
- 2. R. C. Ward, K. L. Kruse, P. T. Williams, N. B. Munro, C. E. Easterly, G. O. Allgood, S. S. Gleason, L. M. Hively, R. J. Toedte, J. J. Dongarra, "Integrated Respiratory System Model for the Virtual Human," Final Report for LDRD #3211-003 (6 Nov 2001).

Increasing breathing difficulty > larger dissimilarities

Inconsistent change for conventional measures

Publications on forewarning of machine failure

1. L.M. Hively, N.E. Clapp, C.S. Daw, "Nonlinear Analysis of Machining Data," ORNL/TM-13157 (Oak Ridge National Laboratory) January 1996.
2. L.M. Hively, "Data-Driven Nonlinear Technique for Condition Monitoring," Proc. Maintenance and Reliability Conference (5/20-22/97) Knoxville, Tn.
3. L.M. Hively, V.A. Protopopescu, N.E. Clapp, C.S. Daw, "Prospects of Chaos Control of Machine Tool Chatter," *ORNL/TM-13283* (June 1998).
4. D.E. Welch, L.M. Hively, and R.F. Holdaway, "Nonlinear Prediction of Fatigue Failure," US Patent Application filed 9/15/99 (all claimed allowed in 3/12/02 action by US Patent Office).
5. L.M. Hively, V. A. Protopopescu, M. Maghraoui, and J.W. Spencer, "Annual Report for NERI Proposal #2000-0109 on Forewarning of Failure in Critical Equipment at Next-Generation Nuclear Power Plants," *ORNL/TM-2001/195* (September 2001).

Collaborations

- **UTKMC (Brian Daley MD/Michael Karlstadt PhD)**
sepsis forewarning via EKG, temperature
- **UTKMC (Pat O'Brien MD/Bob Spencer MD)**
cardiac forewarning via EKG
- **MCO (Dan Olson MD PhD/Jeff Hammersely MD)**
automated sleep staging
- **U Cincinnati/CCHMC (Ton deGrauw et al.)**
pediatric epilepsy forewarning via scalp EEG
- **ViaSys Healthcare (Nicolet Biomedical Inc)**
epilepsy forewarning via EEG
- **Joint proposals with companies, labs**
sleep apnea, epilepsy, cardiac, machines

Examples of Failure Prognostication

<u>Data Provider</u>	<u>Equipment and Type of Failure</u>	<u>Diagnostic Data</u>
1) EPRI (S)	800-HP electric motor: air-gap offset	motor power
2) EPRI (S)	800-HP electric motor: broken rotor	motor power
3) EPRI (S)	500-HP electric motor: turn-to-turn short	motor power
4) Otero/Spain (S)	1/4-HP electric motor: imbalance	acceleration
5) PSU/ARL (A)	30-HP motor: overloaded gearbox	load torque
6) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
7) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
8) PSU/ARL (S)	crack in rotating blade	motor power
9) PSU/ARL (A)	motor-driven bearing	vibration power
10) EPRI (S)	800-HP electric motor: air-gap offset	vibration power
11) EPRI (S)	800-HP electric motor: broken rotor	vibration power
12) EPRI (S)	500-HP electric motor: turn-to-turn short	vibration power
13) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
14) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
15) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
16) PSU/ARL (A)	30-HP motor: overloaded gearbox	vibration power
17) PSU/ARL (S)	crack in rotating blade	vibration power

(S) = seeded fault

(A) = accelerated failure